Active vibration control of piezo-laminated cantilever beam

A THESIS SUBMITTED IN PARTIAL REQUIREMENTS FOR THE DEGREE OF

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CERTIFICATE

This is to certify that the thesis entitled, "**ACTIVE VIBRATION CONTROL OF PIEZO-LAMINATED CANTILEVER BEAM"** submitted by Mr. **JOY BARAL**, Mr. **PEENAK CHATTERJEE** and Mr. **SIDHARTH DAS** in partial fulfillments for the requirement of the award of Bachelor of Technology Degree in Mechanical Engineering at National Institute of Technology, Rourkela is an authentic work carried out by them under our guidance.

To the best of our knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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We express our sincere thanks to Dr T. Roy and Dr. H. Roy to award us with such a wonderful opportunity to present a Project report on “**Active vibration control of piezolaminated cantilever beam**”, which is a recent field of research and development and its application in industries show a promising future in effectively reducing unwanted vibrations in machines and other parts. Our project supervisors were instrumental in the process of bringing this project to its present form. Without their key support, knowledge and experience, procurement of set-up, set-up of project equipment and analysis work would not have been possible.

Contents

Abstract:

In active vibration control the vibration of a structure is reduced by using opposite directional force to the structure. Now a day's active vibration control is frequently being used in aircraft, submarine, automobile, helicopter blade, naval vessel. In this project a smart plate (aluminum plate) with one pair of piezoelectric lamination is used to study the active vibration control. The smart plate consists of rectangular aluminum beam modeled in cantilever configuration with surface bonded piezoelectric patches. The study uses ANSYS-12 software to derive the finite element model of the smart plate. Based on this model, the optimal sensor locations are found and actual smart beam is produced. In this experiment we find a suitable control methodology by which we optimize the controller gain to get more effective vibration control with minimum control input.

Introduction

Active vibration control is defined as a technique in which the vibration of a structure is reduced or controlled by applying counter force to the structure that is appropriately out of phase but equal in amplitude to the original vibration. As a result two opposite force cancel each other and structure stops vibrating.

Techniques like use of springs, pads, dampers, etc have been used previously to control vibration. These techniques are known as "Passive vibration control technique"[16]. They have limitations of versatility and can control the frequencies only within a particular rage of bandwidth hence there is a requirement for active vibration control.

Active vibration control is a modern approach towards vibration control at various places; classic control techniques are becoming too big for modern machines where space is limited and regular maintenance is not possible and if possible, it's too expensive, at such conditions AVC techniques comes handy, it is very cheap requires no manual maintenance and the life expectancy is also much more then the passive controllers.

Active vibration control makes use of smart structure [17]. The system mainly requires actuators, sensors, source of power and a compensator that performs well when vibration occurs. Smart structure are used in the bridges, trusses, buildings, mechanical systems etc. analysis of a basic structure can help in improving the performance of structure under poor working conditions involving beam vibrations

The Major components are

1. Sensor patch- it is bonded to the host structure (beam). It is generally made up of piezoelectric crystals. It senses the disturbance of the beam and generates a charge which is directly proportionally to the strain. Direct piezoelectric is used.

2. Controller- the charge developed by the sensor is given to the controller, the controller lines are charged according to the suitable control gain and charge is fed to the actuator. Controller also forms the feedback functions for the system.

3. Actuator patch- the lined up charge from the controller is fed to the actuator causes pinching action (Or generates shear force) along the surface of the host which acts as a damping forces and helps in the alternating vibration motion of the beam. Converse piezoelectric is used.

The beam is clamped at one end using the set table hence making it a cantilever beam, the excitation is given from the other end, the free end using an exciter, excitation of which can be controlled using a function generator (Producing a wave form of sinusoidal, triangle, Square) and an amplifier. The excitation produces vibrations in the beam which results in the formation of shear stress in the beam, the sensor patch present at the fixed end acts to this shear stress and produces proportional electrical signals which is fed to the computer through the D/A system and finally from the computer the signal is fed to the actuator and it produces opposite shear in the beam and the entire beam is balanced.

Active vibration control finds its application in all the modern day machines, Engineering structures, automobiles, gadgets, sports equipments, ceramics, electronics etc. As it needs only a little actuation voltage hence it does not requires any external power source, the power can be directly derived from the host machine itself. As the electronics is also developing at a very fast rate hence the size of a processor is also reducing, which is very useful in the design of the control system.

In this work a smart plate (aluminum plate) with one pair of piezoelectric lamination is used to study the active vibration control. The smart plate consists of rectangular aluminum beam modeled in cantilever configuration with surface bonded piezoelectric patches. The study uses ANSYS-12 software to derive the finite element model of the smart plate. Based on this model, the optimal sensor locations are found and actual smart beam is produced. In this experiment we find a suitable control methodology by which we optimize the controller gain to get more effective vibration control with minimum control input.

Literature Review

Title: Spacecraft vibration suspension using variable structure output feedback control and smart material.

Authors: Qinglei Hu**,** Guangfu Ma **(**Distinguished Professor of Aerospace Engineering) Department of Control Science and Engineering, Harbin Institute of Technology, CHINA

Vibration reduction is critical problem related to manufacture of floatable spacecraft, which often employs large flexible structures are generally light weight and have relatively low damping for the fundamental and initial model. Further, the frequency associated with these models are low, the vibration control of nodes become an important issue in satellites and other large spacecraft structure.

Active vibration control has been used as a solution for flexible spacecrafts to achieve the degree of vibration or suspension for required precision painting accuracy. Negative feedback control is an effective method for active damping which is the greatest immunity against the destabilizing effects of spillover.

A second critical problem arises that model uncertainties of the flexible spacecraft is governed by partial differential equation as a system of distributed parameters and therefore possesses an infinite number of dimensions , which make it difficult to control.

The paper explores the availability of the variable structure output feedback control (VSOFC)[5] approach to flexible spacecraft for large angle rotational moments with active vibration control using piezo-ceramics. There are three control algorithm viz. constant gain negative velocity feedback controls, positive position feedback, linear quadratic Gaussian control.

The goal of design is to achieve good robustness and distribution rejection, which can be achieved during sliding phase. Therefore, the sliding surface should be large as possible, the reaching time should be small and the boundary should also be small.

A generalized scheme bound or variable structure output feedback control and altitude controller VSOFC acting on hub and design of independent flexible control system using piezo-ceramics. Three different algorithms namely GNUF, PPF & LOG control are designed acting on flexible appendage and both simple and multimode vibrations are studied [5].

Title: Optimum location of sensors and actuators for the control of flexible structure.

Authors: Jaques Lottin, Fabian Formosa, Mihal Virtosu, Laurent Brunett

The work deals with the problem of efficient location of sensors and actuators encountered in the domain of active vibration of flexible structure. The optimum solution depends on the control scheme. Usage of the “optimal” before the word location means that there is a criterion that allows the comparison between several situations in order to determine the best choice. Complications occur in the problem as:

-several criteria must be considered simultaneously, one for the sensors, one for actuator and one for the quality of rejection along the beam.

-models are complex because of their large size and it is not always possible to get an optimized solution.

To illustrate the influence of actuator and sensor location, we consider particular criteria called deg5, computed by stimulation experiments were carried out on a fixed-free steel beam where the input was a force and output was position. Dynamic behavior was found to be changing according to the sensor and actuator position as their mass was taken account into while building a model.

$$\deg 5 = \sum_{i=0}^{2n} \frac{\gamma i}{\sigma(\gamma i)} \times \sqrt[2\pi]{\prod_{i=0}^{2n} \gamma i} \quad [4]$$

$\gamma i = \text{eigen values}, \sigma = \textit{standard deiviation}$

The state representation is obtained using a finite element model of the system. To do that ANSYS software is used to build a general FEM description of the system then the structure dynamic tool box is used to derive a state space model, after activating approximate nodes corresponding to the location of actuators and sensors.

After analyzing the qualitative information of the two simultaneously it was found that the collocation is not good at all but the choice of force and position as input and output is not appropriate for PPF control.

The stimulation analysis was carried in parallel with experiment. In experiment, the quality of rejection with respect to actuator and sensor location was determined. A second mock-up was built with three PZT patches acting as sensor or actuator, plus an optimal sensor added to the system, tests were carried out using specific control scheme.

This algorithm consists in a compensation of sinusoidal disturbances by computing appropriate sinusoidal actions corresponding to most relevant frequencies in output range. Main results are summarized in the table [4] below.

ACTUATOR	SENSOR	PZTO	PZTM	OPTICAL
PZTO	PZTM		VG	G
PZTO	Optical		G	VG
PZTM	PZTO	Vg	Vb	N
PZTM	PZTM	n	Vb	G
PZTM	Optical	g	Vb	VG

The first and second columns respectively represent the devices that are used as actuators and sensors for control system. It can be observed that very good rejection is always obtained at the location of the sensor which is used to give information to control algorithm. After analyzing, it was concluded that the performance is not satisfactory while using the center PZT and anyone of the beam at the extremities of the beam [4].

Title: Active vibration control of composite beam with piezo-electronics: A finite element model with third order theory.

Author: X.Q.Peng, K.Y.Lam, G.R.Liu. Depertment of mechanical engineering, National institute of Singapore.\

A finite element model with third order theory is used for active vibration control and active position control of composite beam with distributed piezoelectric sensor and actuators. Piezoelectric materials such as Lead Zirconate Titanate (PZT), exhibit mechanical deformation when subjected to an applied electric field, which is called the converse piezoelectric effect and also generate voltage or charge when subjected to a force or deformation. Third order laminated theory is developed for the active vibration control of composite beam with distributed piezoelectric sensor and actuators. The piezoelectric equation is:

$[D] = [e]\{\varepsilon\} + [\varepsilon]\{E\}$ [9]

$\{\sigma\} = [Q]\{\varepsilon\} - [e]^T\ [E]$ Where, $[D]$=Electric displacement vector,$[e]$=piezoelectric constant matrix, $\{E\}=$ Electrical field vector, $\{\sigma\}$= stress vector, $\{\varepsilon\}$=strain vector, $[\varepsilon]$= permittivity matrix, $[Q]$=elastic stiffness matrix, $[e]^T =$ Transpose of $[e]$.

The displacement field based on the third order beam theory of Reddy is given by:

$$U(x,z,t) = U_1 0\ (x,t) + Z \emptyset_1 x\ (x,t) - \alpha Z \uparrow 3\ (\emptyset_1 x + (\partial w_1 0)/\partial t\ )$$ [9]

$$w(x,y,t) = w_0(x,t)$$ [9]

Where ' U' and 'W' are the displacement components in 'x' and 'z' direction.

The dynamic equation of a piezoelectric structure can be derived by Hamilton's principal:

$$\delta \int_{t_1}^{t_2} [T - U + W] dt = 0$$ [9]

Where 'T' is the kinetic energy, 'U' is strain energy; 'W' is work done by applied force.

Since no external electrical field is applied to the sensor layer and as charge is collected only in the thickness direction, only the electric displacement D_3 is of interest and can be derived by the equation:

$$D_3 = e_3 . \varepsilon$$ [9]

Hence the closed circuit voltage measured through the electrodes of a sensor patch in the K^{th} layer is:

$$q(t) = \frac{1}{2}\left[\iint_{s_2 (z=zk)} D_3 ds + \int_{s_2 (z=zk+1)} D_3 ds\right]$$ [9]

The distributed sensors generate a voltage when a structure is oscillated and this signal is fed back in to the distributed actuator using a control algorithm. The actuating voltage under a constant gain control algorithm can be expressed as:

$$V^a = G_i V_s = G_i G_i \frac{dq}{dt}$$ [9]

In the case of shape control all the piezoelectric on the upper and lower surface of the beam are used as actuator. Due to the converse piezoelectric effect, the distributed piezoelectric actuator contract or expand depending on negative or opposite active voltage. For an upward displacement, the upper actuators need a negative voltage and lower actuators need a positive one [9].

Title: Active vibration control of smart plate

Authors: Yavuz Yaman, Tarkan Callskan, Volkan Nalbantonglu

Smart plate consists of a rectangular aluminum plate modeled in cantilever configuration with surface bonded piezoelectric sensor and electric patches. The patches are symmetrically bonded on the top and bottom surface now using ANSYS, a model is prepared and experiments are conducted with it to find out the influences of actuator placement and size on the response of smart plate and determine the maximum admissible piezoelectric voltage.

Now the various parameters are discussed which will be affecting the response of the smart plate.

-Effect of actuator placement –The actuators used is BM 500 and HS dimensions are (25*25*0.5), it is used on aluminum plate, the actuators are placed using modal analysis and identically polarized patches are assumed to be bonded symmetrically on top and bottom. Now to find the influence two cases are considered, the positioning of the patches is in x-y co-ordinate system and they are changed while keeping the distance between them constant. As the patches are placed near the root (y=0), response increases. But when the patches are moved in x-direction then there is no noticeable change in response.

-Influences of actuator sizes- The effect of increase in size of actuator on the response are investigated in terms of change in convergent ratio, which is defined by the ratio of the area converged by piezoelectric sensors. The piezoelectric actuator of 300 V is provided and found out that increase in size increases the energy transmitted to the smart plate giving rise to the response for the specified piezoelectric actuation value. It also increases the stiffness of the plate.

-Maximum admissible piezoelectric actuation- Piezoelectric materials are bitter and have tensile strength in order of 63 MPa. Therefore the stress in the actuators can be critical in adverse applications. In order to determine the maximum possible piezoelectric actuation valve, the von mises stresses developed in the actuator should be investigated prior to the operation. It was found to be of the order of 1 MPa. For normal operation (200-300 V), the piezoelectric is not expected to fail. [2]

Title: Active Vibration Control of composite sandwich beams with distributed piezoelectric extension-bending and shear actuator

Authors: S.Raja, G.Prathap, P.K.Sinha (Dept. of Aerospace Engineering, IIT Kharagpur)

The shear actuator induce distributed force/moments in the sandwich beam in contrast to the extension-bending actuators, which develop only concentrated force/moment and is found more efficient in actively controlling vibration. Actuator thickness & position play an important role in deciding the performance. The extension-bending actuator produces more transverse deflection than the shear actuator. We can observe that moderately thin shear actuators is found to be more efficient and also the face laminated thickness has a significant effect on the efficiency of the shear actuator [13].

Title: A spline based Reconstruction for active vibration control of a flexible beam

Author: R. Setola (Italy)

The reconstructor uses a spline shaped function to interpolate the available measurements and to take into account the boundary condition. The spline functions introduce a sort of spatial filtering on the high frequency mode and thus increase the robustness of the control scheme against spillover. Reconstructor joined to a suitable controller is able to reduce vibration of beam subjected to persistent multi-frequency disturbance acting at unknown beam abscissa. Thus by using this we can reduce the noise generated by the flexible structure when they are excited by some external pseudo-periodic cause [8].

Title: Optimal location piezoelectric sensor and actuator for flexible structure

Author: Le'o Lenquist da Rocha, Samuel da Silva, Vicent lopes Jr (Paulista State University-UNESP, Brazil)

Active Vibration control by smart material technology is increasing day by day. To obtain optimized control performance, actuator and sensor must be placed at locations to excite the desired mode more effectively. It may be modeled by finite element method using MATLAB, ANSYS etc. H^{∞} norm each sensor and actuator position is determined for selected modes of plate and computed using linear matrix inequalities technique. PZT elements are positioned at the optimal position using two first mode of structure [6].

Title: Active Vibration Control of Residual Vibrations of a cantilever smart beam.

Author: Zeki KIRAL, Levent MALGACA, Murat AKDA˘G *Dokuz Eyl¨ul University, Faculty of Engineering, ˙Izmir-TURKEY*

The dynamic response of the beam is calculated by using the finite element method in order to design a suitable control technique and numerical results are verified by vibration measurements.

Two laser displacement sensors are used to measure the dynamic response of the beam The moving load is obtained by pressured air directed to the beam vi nozzle. In this case the suppression of the residual vibration that occurs after the moving load has left the beam is considered as main subject. Active vibration control of a cantilever smart beam is considered both experimentally and numerically. The simulation of closed loop vibration control with displacement feedback is achieved by using a commercial finite element package [7].

Title: Hybrid wave/mode active control of bending vibrations in beams based on the advanced Timoshenko theory. (Journal of Sound and Vibration 322 (2009) 29–38)

Authors: C Mei, Department of Mechanical Engineering, University of Michigan-Dearborn, USA

Due to demand for mechanical structures to be lighter and faster, there has been increasing interest in Active vibration control in recent years. In this paper, a hybrid approach consisting of complementary wave and mode-based control is described on Timoshenko theory. In modal Active Vibration Control, the aim is to control the characteristics of modes of vibration i.e their damping factors, natural frequency or mode shapes. Active wave control aims to control the distribution of energy in structure by either reducing the transmission of waves from one part of the structure to another or by absorbing the energy carried by other waves. In proposed hybrid approach, wave control is first designed and is targeted at higher frequencies. Two control strategies there, one optimally absorbs the vibrational energy and the other adds optimal damping to structure. Modal control is then designed for the lower modes of structure based on modified equation of motion of structure-plus-wave-controller. After the implementation of wave control, the equation of motion of the system is modified. Hybrid approach exhibits better broadband active vibration control performance than the cases with either modal or wave control alone. While control design based on the classical Euler-Bernoulli model theory is only applicable to slim beams, the present design based on the advanced Timoshenko model is suitable for deep as well as slim beam elements [12].

Title: Active vibration control of a flexible beam mounted on an elastic base.

Author: Chih-Liang Chu (**a**), Bing-SongWu (**a**), Yih-Hwang Lin (**b**), (**a**) *Department of Mechanical Engineering, Southern Taiwan University of Technology, Tainan 710, Taiwan, Republic of China.* (**b**)*Department of Mechanical and Mechatronic Engineering, National Taiwan Ocean University, Keelung 202, Taiwan, Republic of China*

This paper investigates the Active vibration control of a flexible beam mounted on an elastic base. Beam system is analyzed using a finite element approach. The study utilizes the independent modal space control (IMSC) method for active control of a flexible beam supported on elastic base. Basic principle of IMSC method is that it transforms the coupled system dynamic equations into the decoupled modal space and thereafter applies a process of feedback control to each decoupled mode. In order to improve analysis accuracy the study considers Timoshenko beam theory for system analyzed. The system equation are first expressed as state-space equations then decoupled. The IMSC method uses the characteristics of left/right modal matrices, R & L, to decouple a coupled system. The modal control force is obtained from control design in modal space. The analysis using the Timoshenko beam theory is examined with a total of 32 finite elements being used. Numerical results are compared with those obtained using ANSYS. The proposed control strategy is not only capable of controlling a single vibration mode, but also two modes while using one actuator. [11]

Title: Active Vibration Control of Flexible Steel Cantilever Beam Using Piezoelectric Actuators

Author: Juntao Fei, Department of Mechanical Engineering, University of Akron, USA

Considerable attention has been devoted recently to active vibration control using intelligent materials as actuators. This paper presents results on active control schemes for vibration suppression of flexible steel cantilever beam with bonded piezoelectric actuators. The PZT patches are surface bonded near the fixed end of flexible steel cantilever beam. The dynamic model of the flexible steel cantilever beam is derived. Active vibration control methods, such as optimized parameter PID compensator, strain rate feedback control are investigated and implemented using *xPC* [3] Target real time system. Experimental results demonstrate that the proposed methods achieve effective vibration suppression results of steel cantilever beam [3].

Title: ACTIVE VIBRATION CONTROL OF A SMART BEAM

Author: Yavuz Yaman (1), Tarkan Çalışkan (1), Volkan Nalbantoğlu (2), Eswar Prasad (3), David Waechter (3) (1.Department of Aeronautical Engineering, Middle East Technical University, Ankara, Turkey 2.ASELSAN Electronics Industries, Ankara, Turkey 3.Sensor Technology Limited, Collingwood, Ontario, Canada)

The study presents an active vibration control technique applied to a smart beam. The smart beam consists of an aluminum beam modeled in cantilevered configuration with surface bonded piezoelectric (PZT) patches. The study uses ANSYS (v5.6) package program. The study first investigates the effects of element selection in finite element modeling. The effects of the piezoelectric patches on the resonance frequencies of the smart structure are also shown. The developed finite element model is reduced to a state-space form suitable for a controller design. The work then, by using this reduced model, presents the design of an active vibration controller which effectively suppresses the vibrations of the smart beam due to its first two flexural modes. The vibration suppression is achieved by the application of $H\infty$ controllers. The effectiveness of the technique in the modeling of the uncertainties is also presented [1].

Objective and Scope of Work

1) To develop a suitable control methodology which optimizes the controller gain so that more effective vibration control can be achieved with minimum control input

2) To study the stability analysis for collocated and non-collocated optimal position of PZT sensor and actuator

3) To detect the damages such as debonding between substrate and piezo-patches delamination between the interfaces of substrate

4) To validate the numerical results with experimental work for real life application

In spacecrafts, automobiles, helicopter, bridges, marine applications [15] we use active vibration control techniques as it can control the frequencies within a particular range of bandwidth. Working machinery is a major source of vibration in marine vessels and considerable effort is devoted in developing isolation system that reduces transmission to hull. This is partly for improving crew and passenger comfort, but in case of naval vessels it is primarily to reduce the associated acoustic signature and hence the vulnerability to detection by hostile sensors such as acoustic mines or passive sonar. A particular problem associated with machinery isolation in marine environment is structural resonance. This occurs both in the machinery support structure and in the hull. Such resonance leads to very high forces transmitted across machinery mounts where resonant frequencies coincide with modes of the hull. Passive solutions have limited performance particularly at lower frequencies. As a result there has been considerable interest in the use of active vibration control methods for machinery mounting structural vibration control.

In aircrafts, spacecrafts, automobiles, helicopters, active vibration control is gaining momentum. Of late the Japanese have started applying active vibration control techniques to long-span bridges.

Finite Element Modeling On ANSYS 12.0

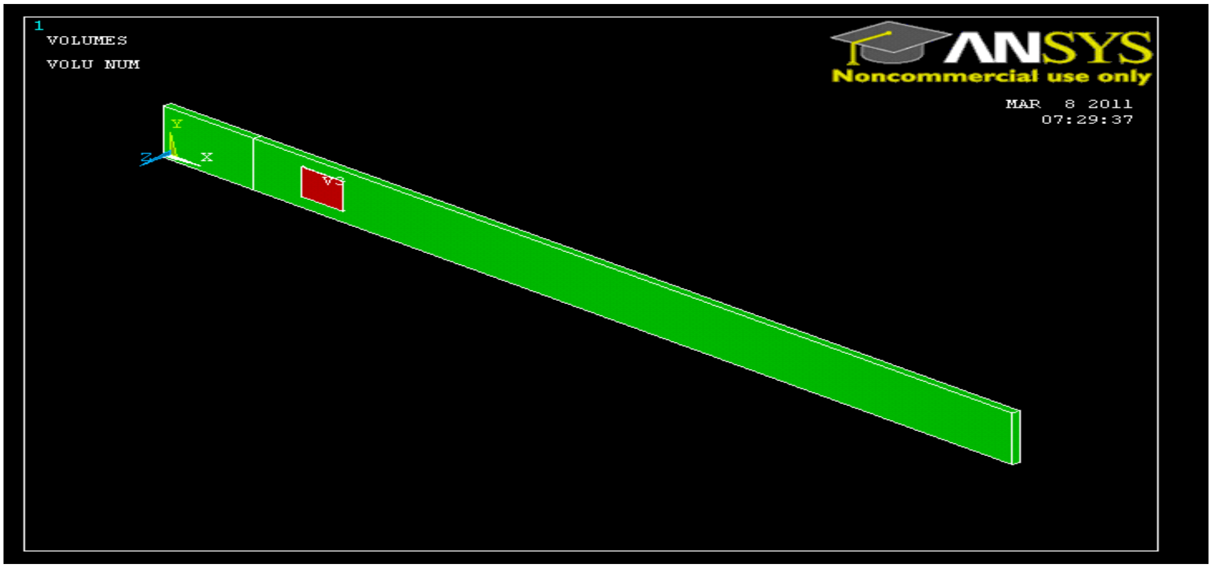

Figure 1 – A smart beam

In the theoretical analysis we used ANSYS-12 software to derive the finite element model of the smart beam. From this analysis we can determine the optimal position and size of the actuator and sensor. We also determine the maximum admissible actuation voltage and the maximum deflection the beam. Based on this model the smart beam is produced in figure 1. This result of the smart beam is then used in the determination of the single input and single output system model. By this model a single input/single output H_∞ controller is designed to suppress the vibrations due to the first two flexural modes of smart plate. At the initial stage of design, the finite element model is sufficient which allows determining the location, size of an actuator and its power requirement.

In the modeling and analysis of piezoelectric crystal typical finite element used was (SOLID5), which has piezoelectric capacity in three dimensional couple field problem. Like other structural solid elements, this element has three displacement degrees of freedom per node. In addition to this degree of freedom the element has also potential degree for the analysis of the electromechanical coupling problems. Piezoelectric actuator inherently exhibits anisotropic and yield three-dimensional spatial vibration in their response to the piezoelectric actuation.

The models developed for the passive portion should include consistent degree of freedom at the location where these elements interface. For modeling the passive portion of the smart structure solid element used is (SOLID45). The passive portion is made of aluminum. In these modeling we could use shell element as (SHELL99) also. But experimental results shows that the hybrid solid -solid model yielded results are closer to the experimental values than ‘hybrid shell-solid model. So solid –solid modeling is more precious.

Young’s modulus for the passive portion (Aluminum beam) is (E) =69GPa (69×10^{9} N/ m^2). The poison’s ratio of the beam is taken (ϒ) =0.33 and the density of the aluminum beam is 2710 Kg/m^3. The damping coefficient of the aluminum was taken as 0.0004. The dimension of the passive part (aluminum beam) is (310×26×2.6) mm*mm*mm and dimensions of the PZT is (15×15×0.5) mm*mm*mm.

In the modeling first the passive block was created and then the two patches were placed over it. The block (vol 1) is made of the material-1(SOLID45) and the two patches (vol2 & vol3) are of same material-2(SOLID5). Next the meshing is done on the two types of materials. Meshing is the process to divide the whole matrix in small-small parts. As a result we can get the exact amount of force, displacement etc. for each small part and the result become more accurate. As one portion of the beam remain fixed (there will be no displacement), we make that portions degree of freedom zero. Actually we arrest that portion. Then in the load step option we give the frequency in 100 sub-steps (0.0 Hz to 100.0 Hz). The damping constant ratio for aluminum is 0.0004. Next we apply a constant force of 9 N on the middle node of the cantilever edge. The direction of the force is positive Z direction.

At the solution we find the result that the maximum displacement value 0.00273 m. The value of maximum shear stress is 0.260×10^{8} N/ M^2 and it is acting on the node number 49.

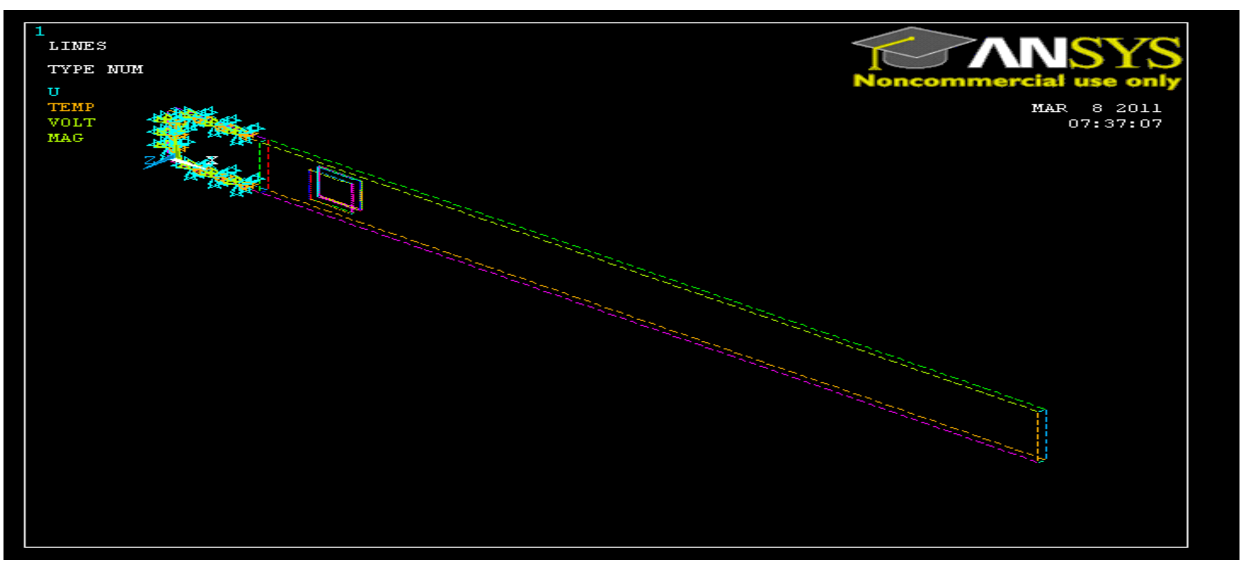

Figure 2

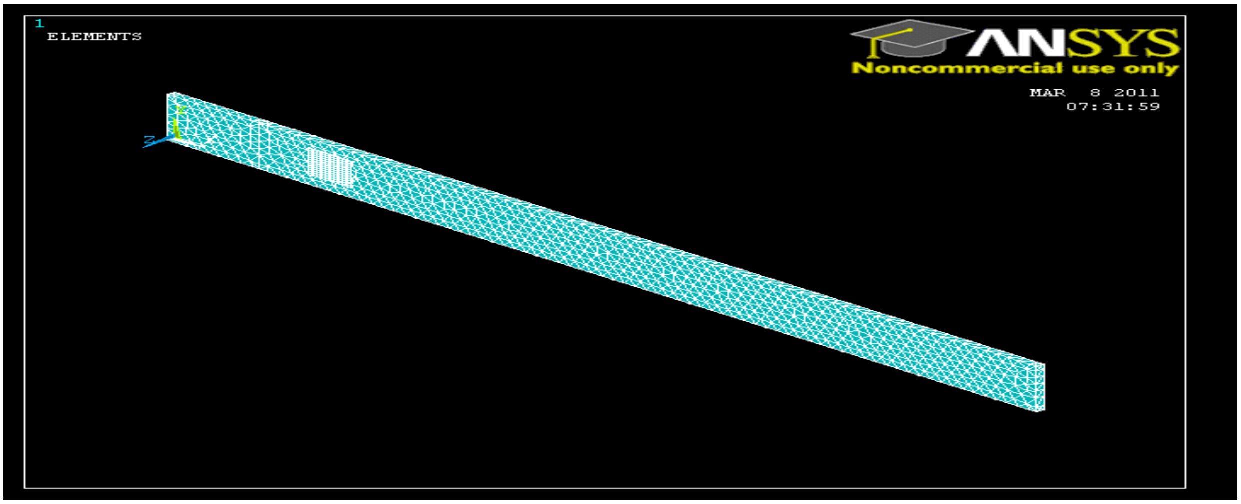

Figure 3

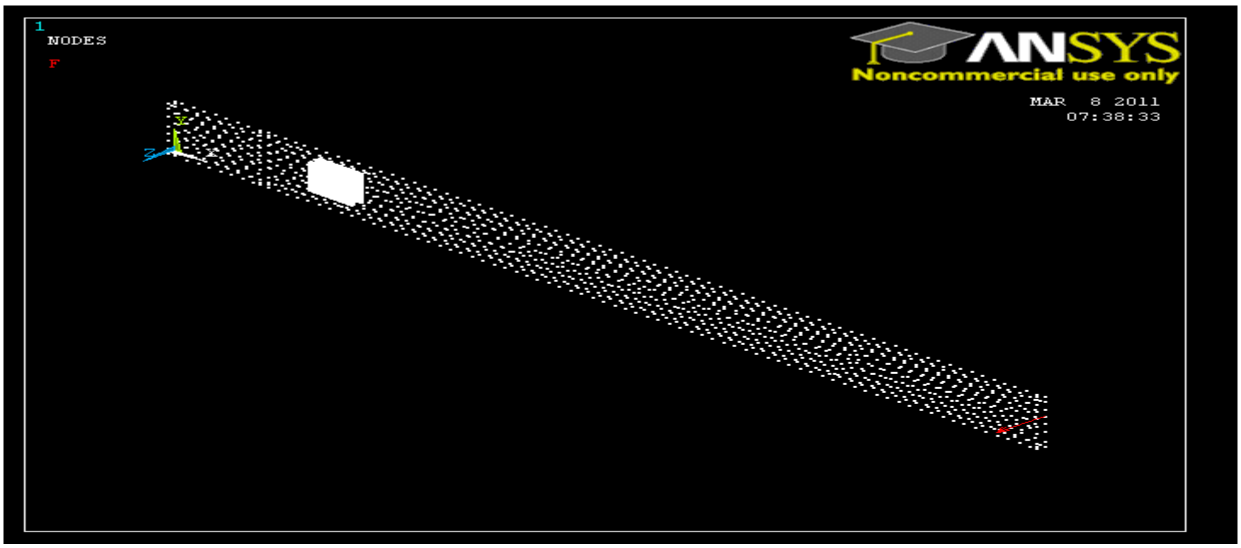

Figure 4

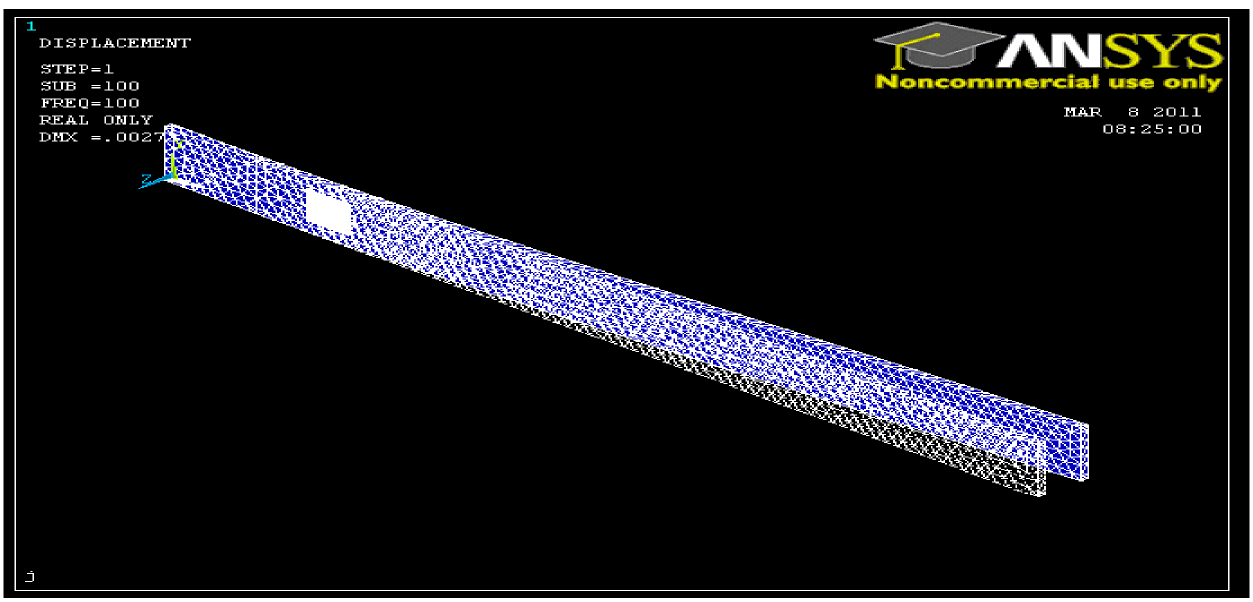

Figure 5

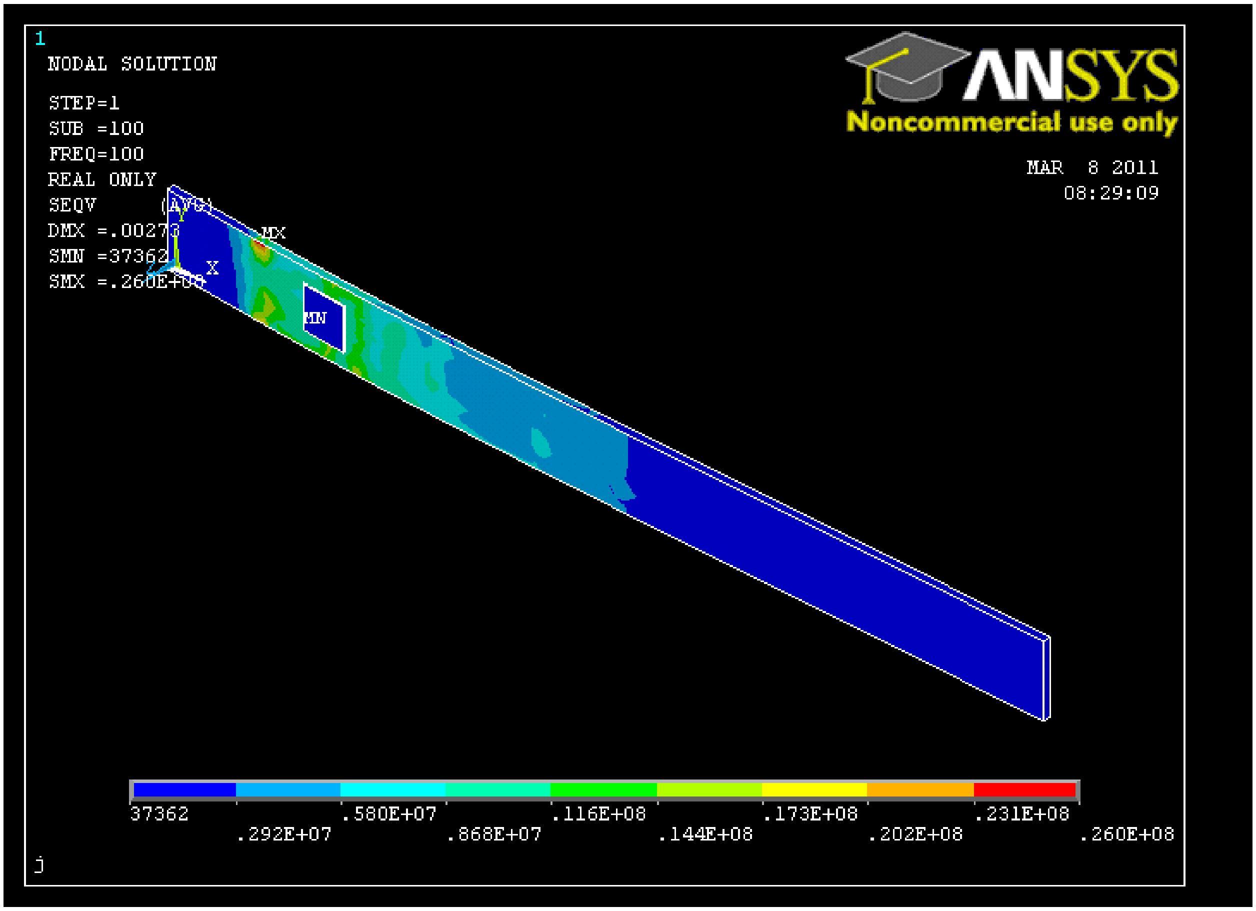

Figure 6

Experimental Setup

The standard experimental setup for the active vibration control consists of several parts described below:-

Aluminum Beam- This is the object on which the experiments are done and our findings will be based. It is a simple beam with a certain density and strength and dimension (31×2.5×0.5) cm.

Set Table- As the beam has to be made a cantilever beam hence we need to clamp it on set table, a set table is a modern clamping apparatus on which we can make adjustments and move it in any axis, even the rotation of the beam is possible.

Sensor Patch- Sensor patch is the material which is attached to the fixed end of the beam and is responsible for the sensing of the stress produced in the beam and generate voltage proportionally, the current produced is called piezoelectric current and it is called so because it is generated from pressure. The material used is generally PZT (Lead zirconate titanate) or PVDF (Polyvinylidene fluoride). PZT is used in our setup and it is made up of Perovskite (Pv) which is a calcium titanium oxide mineral species composed of calcium titanate, with the chemical formula $CaTiO_3$. When there is a deflection in the host structure then due to the stress induced in sensor patch the crystals present in the sensor realigns them self and in the process develop piezoelectric current though this current is very less but if we combine many crystals together then we can generate enough amount of power.

Actuator Patch- When a certain amount of voltage is provided to the sensor then it produces the opposite effect and acts like an actuator, actuator is used to produce mechanical stress in the host structure, this voltage comes from the control system which gets the input from the sensor. For proper actuation in the beam, the actuator is located at the fixed end as highest amount of stress is produced in that part also the bending moment is maximum there.

Function Generator – An electronic function generator is used to generate a function usually sinusoidal, Square or triangular wave form, the profile of wave form generated lets us induce similar kind of vibration In the beam.

Amplifier- the signal received from the function generator is very weak and is no enough to drive the exciter, hence the function generator is coupled with an amplifier where the signals are amplified and finally fed to the exciter.

Data Acquisition system- D/A system is responsible for the encryption of the input/output system, the signal which we receive form the sensor is an electrical signal, and is not compatible with the computer, hence the D/A system is used to convert this signal into acceptable form and then fed to the computer, and after the calculation in computer, the signal is again given to the D/A system to again convert it into suitable format before it is fed to the Actuator.

Computer- A computer with the control software is used to monitor the signal, here we can see the strength of the signal and if required vary it according to our need, all the data can be stored in the computer for future references.

Oscilloscope – a modern digital oscilloscope is used to monitor the signal from the sensor, the part of oscilloscope is very important as we can see the pattern of the signal forming in the sensor and also we can measure various parameters using the oscilloscope such as Voltage, Gain etc.

Scanning laser Doppler vibrometer- it is a device used for measuring the maximum deflection in the beam at the free end.

The Experiment

The aluminum beam (substrate) is fixed at one end on the set table and other end is hanging freely hence is a cantilever beam, from the end we will give under control vibration and this is accomplished by using a exciter the function of the exciter is to produce under control vibration on the beam and the nature of the vibration will depend upon the input signal form the function generator, whatever will be the nature of the waveform similar kind of vibration will be produced in the beam, the function generator is used to generate the desired wave form which can be either of sinusoidal, triangle, Square the rang of the frequency can be adjusted and can be set anywhere between 1Hz to 1000 KHz but as our exciter has limitations so we can only set the frequency between 1Hz to 1Khz the frequency is high but the amplitude of the wave form is very low to produce any notable vibration in the beam hence an amplifier is used to amplify the signal the range of amplification can be varied using the knob provider at the amplifier but we should not amplify more than the safe limit of the exciter and also the quality of the vibration will be degraded and also the PZT patches may be damaged. Vibration produces deflection in the beam which is maximum at the free end, and to measure this deflection scanning laser Doppler vibrometer is used, it is very accurate and can record even the smallest deflection which is produced in the beam.

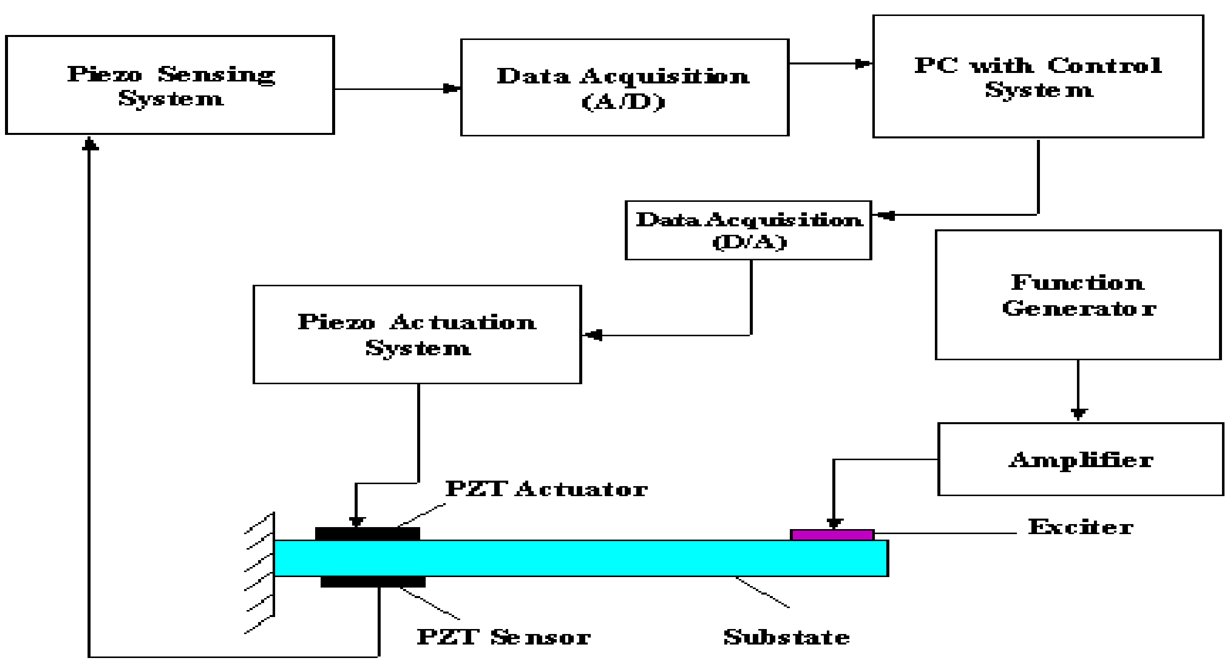

Fig. 7 Experimental setup [14]

On doing the modeling of this experiment in ANSYS we computed the area of stress formation an interesting observation which was made was that the maximum stress which was developed in the beam was not where it was clamped, it was little away from it, hence we will attach our sensor and actuator here because the sensor will produce the correct voltage only here as the current developed is directly proportional to stress hence we will get the maximum current here. The actuator which is responsible to produce opposite stress in the beam is also located at the location of maximum stress formation so that it may control the vibration more efficiently. The signal which we get from the sensor is in electrical in nature and cannot be fed to the computer directly hence the signal has to be modified to be made compatible with our control system hence we use data acquisition system, this convert the signal from analog to digital as computer can only read and interpret digital signals so encryption satisfied that, now the signal is given to the computer system which is having a suitable software which facilitates in the manipulating and storing of the data's, also the health of the patches can be checked using this software. From the software the signal is fed to data acquisition system again to convert again to analog electrical signals and from here finally the signal is fed to the actuator which actuates a stress in the beam, to understand this effect we can take an example of sine wave which initiates form +1, this sine wave is the vibration induced in the beam by the exciter now to control this vibration the actuator have to actuate a signal which will be of the same magnitude but will be of opposite phase hence the actuator will actuate a wave which will start from -1 hence when both of this vibration meet with each other then the cancel out each other, which results in the damping of the beam. The whole process can be monitored in an oscilloscope which can be attached to the sensor and the actuator at the same time, the electrical signal produced by the sensor can be monitored in the oscilloscope and the pattern of wave formation can be noted down.

RESULTS

The electrical signal generated by the piezo electric patch due to the vibration was monitored in the oscilloscope and all the parameters were recorded, as in this experiment we are only concerned with the maximum voltage which is produced by the sensor so we will concentrate our findings on the same and plot the graph with the gathered data. Total we recorded 6 observations with frequency as a variant the observation table of which is given below:-

1. Frequency = 10×1.25=12 Hz

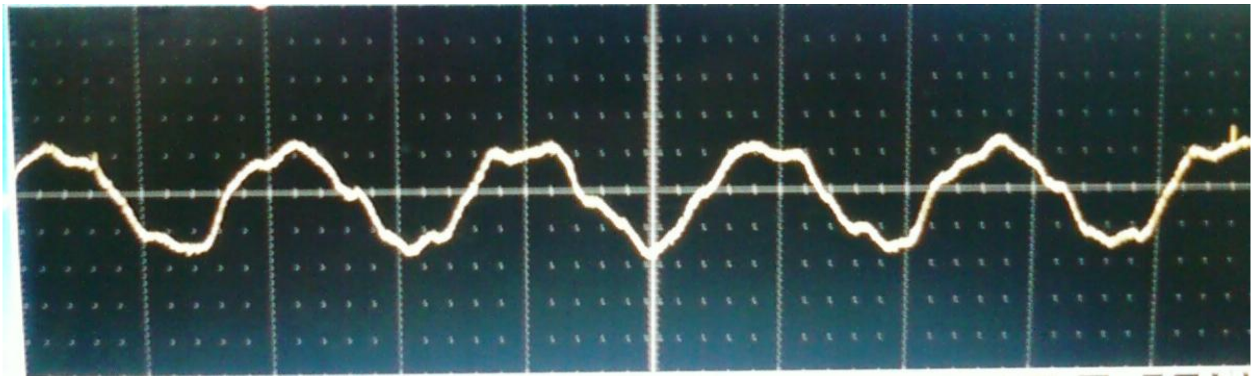

Fig. 8- Showing the signal pattern formed by the input frequency of 12 Hz

Period (ms)	72.03	Frequency (Hz)	13.88
+width (ms)	38.93	-width (ms)	33.10
Burst W (ms)	330.1		
Rise (ms)	11.92	Fall (ms)	13.04
+duty (%)	54.05	-duty (%)	45.95
+over (%)	30.19	-over (%)	28.30
High (v)	1.120	Low (v)	-1.000
Max (v)	1.760	Min (v)	-1.600
Amplitude (v)	2.120	Pk-Pk (v)	3.360
Mean (mV)	166.5	Cycle mean (mV)	79.93
RMS (mV)	1.122	Cycle RMS (mV)	970.0
Area (mVs)	66.59	Cycle area (mVs)	5.758

Table 1

By applying the frequency of 12.5 Hz we get the above data's, the maximum voltage which the piezo electric material produces is 1.760V and the maximum amplitude of the signal is 2.120 V, the peak to peak voltage was found out to be 79.93 mV and the RMS value of the voltage was found to be 1.122 mV

2. Frequency = 10×1.5=15 Hz

Fig. 9- Showing the signal pattern formed by the input frequency of 15 Hz

Period (ms)	60.70	Frequency (Hz)	16.47
+width (ms)	32.10	-width (ms)	28.60
Burst W (ms)	369.0		
Rise (ms)	10.48	Fall (ms)	14.35
+duty (%)	52.88	-duty (%)	47.12
+over (%)	22.73	-over (%)	18.18
High (v)	1.200	Low (v)	-1.440
Max (v)	1.800	Min (v)	-1.920
Amplitude (v)	2.640	Pk-Pk (v)	3.720
Mean (mV)	126.5	Cycle mean (mV)	95.35
RMS (mV)	1.134	Cycle RMS (mV)	1.135
Area (mVs)	50.59	Cycle area (mVs)	5.788

Table 2

By applying the frequency of 15 Hz we get the above data's, the maximum voltage which the piezo electric material produces is 1.800V and the maximum amplitude of the signal is 2.640 V, the peak to peak voltage was found out to be 3.720 mV and the RMS value of the voltage was found to be 1.134mV

3. Frequency = 10×1.75=17.5 Hz

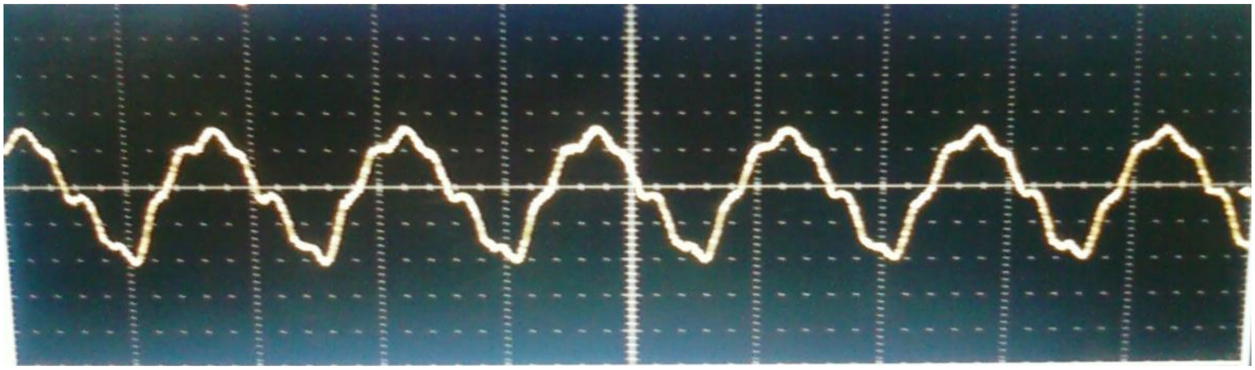

Fig. 10- Showing the signal pattern formed by the input frequency of 17.5 Hz

Period (ms)	43.18	Frequency (Hz)	23.16
+width (ms)	20.53	-width (ms)	22.65
Burst W (ms)	371.3		
Rise (ms)	4.810	Fall (ms)	10.88
+duty (%)	47055	-duty (%)	52.45
+over (%)	23.81	-over (%)	41.67
High (v)	1.640	Low (v)	-1.720
Max (v)	2.440	Min (v)	-3.120
Amplitude (v)	3.360	Pk-Pk (v)	5.560
Mean (mV)	117.2	Cycle mean (mV)	88.47
RMS (mV)	1.505	Cycle RMS (mV)	1.506
Area (mVs)	46.89	Cycle area (mVs)	3.820

Table 3

By applying the frequency of 17.5 Hz we get the above data's, the maximum voltage which the piezo electric material produces is 2.440V and the maximum amplitude of the signal is 3.360 V, the peak to peak voltage was found out to be 5.560 mV and the RMS value of the voltage was found to be 1.505 mV

4. Frequency = 10×20=20 Hz

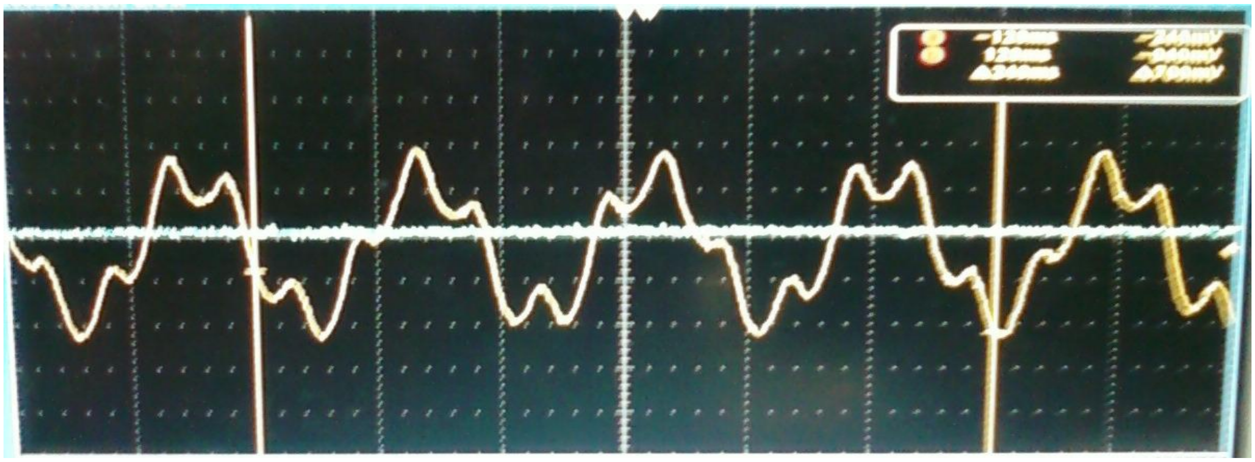

Fig. 11- Showing the signal pattern formed by the input frequency of 12 H

Period (ms)	37.52	Frequency (Hz)	26.65
+width (ms)	15.85	-width (ms)	21.67
Burst W (ms)	377.5		
Rise (ms)	4.477	Fall (ms)	4.189
+duty (%)	42.24	-duty (%)	57.76
+over (%)	31.15	-over (%)	90.16
High (v)	1.800	Low (v)	-640.0
Max (v)	2.560	Min (v)	-2.840
Amplitude (v)	2.440	Pk-Pk (v)	5.400
Mean (mV)	123.9	Cycle mean (mV)	86.19
RMS (mV)	1.611	Cycle RMS (mV)	1.622
Area (mVs)	49.54	Cycle area (mVs)	3.234

Table 4

By applying the frequency of 20 Hz we get the above data's, the maximum voltage which the piezo electric material produces is 2.560V and the maximum amplitude of the signal is 2.440 V, the peak to peak voltage was found out to be 5.400 mV and the RMS value of the voltage was found to be 1.611 mV

5. Frequency = 10×2.250=22.5 Hz

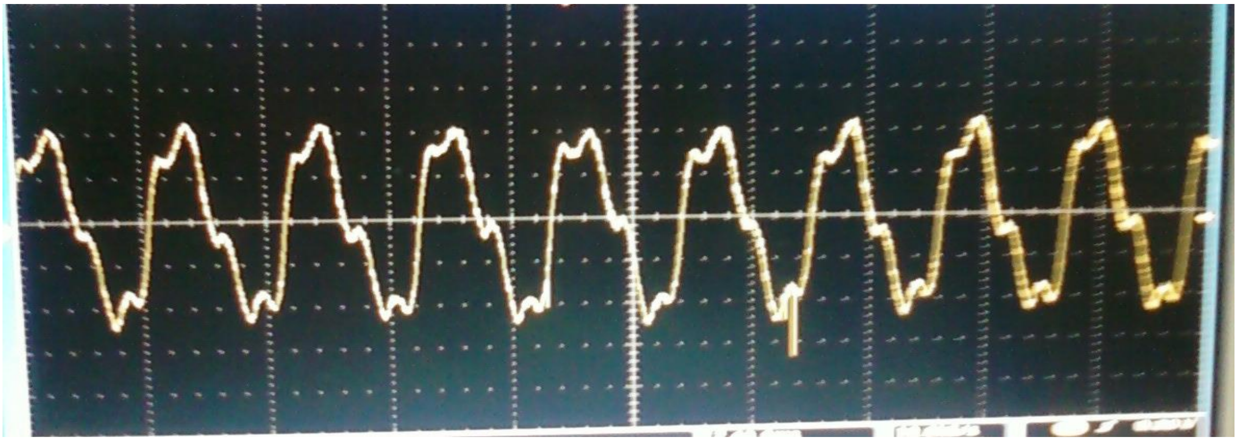

Fig. 12- Showing the signal pattern formed by the input frequency of 122.5 Hz

Period (ms)	5.598	Frequency (Hz)	178.6
+width (ms)	5.511	-width (ms)	87.11
Burst W (ms)	378.0		
Rise (ms)	15.93	Fall (ms)	13.72
+duty (%)	98.44	-duty (%)	1.556
+over (%)	0.000	-over (%)	0.000
High (v)	5.320	Low (v)	-3.760
Max (v)	5.320	Min (v)	-3.760
Amplitude (v)	9.080	Pk-Pk (v)	9.080
Mean (mV)	89.58	Cycle mean (mV)	2.071
RMS (mV)	1.905	Cycle RMS (mV)	2.335
Area (mVs)	35.83	Cycle area (mVs)	11.59

Table 5

By applying the frequency of 22.5 Hz we get the above data's, the maximum voltage which the piezo electric material produces is 5.320V and the maximum amplitude of the signal is 9.080 V, the peak to peak voltage was found out to be 9.080 mV and the RMS value of the voltage was found to be 1.905 mV

Taking the value of Vmax from the above table and corresponding frequency and making a chart we get

V_{max} (V)	1.760	1.80	2.080	2.440	2.560	5.320
Frequency (Hz)	12.5	15	17.5	20	22.5	25

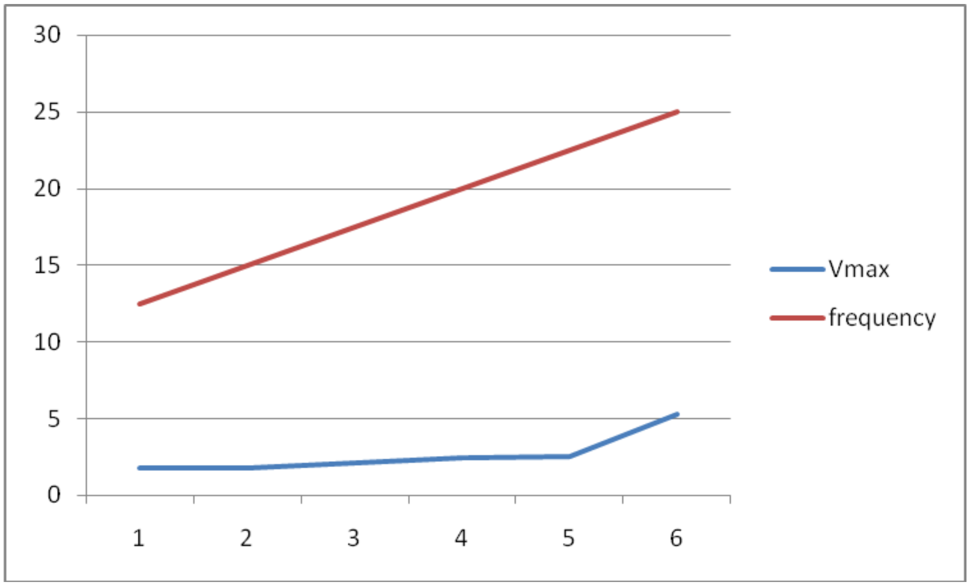

Chart 1 showing the curve formed between the maximum voltage and frequency

Amplitude	Frequency	RMS	Area	Mean	Voltage
2.12	12.5	1.112	66.59	166.5	1.12
2.64	15	1.134	50.59	126.5	1.8
3.36	17.5	1.505	46.89	117.2	2.44
2.44	20	1.611	49.54	123.9	2.56
9.08	22.5	1.905	35.83	89.58	5.32

Table 7- All the major parameters obtained as output from the input frequency

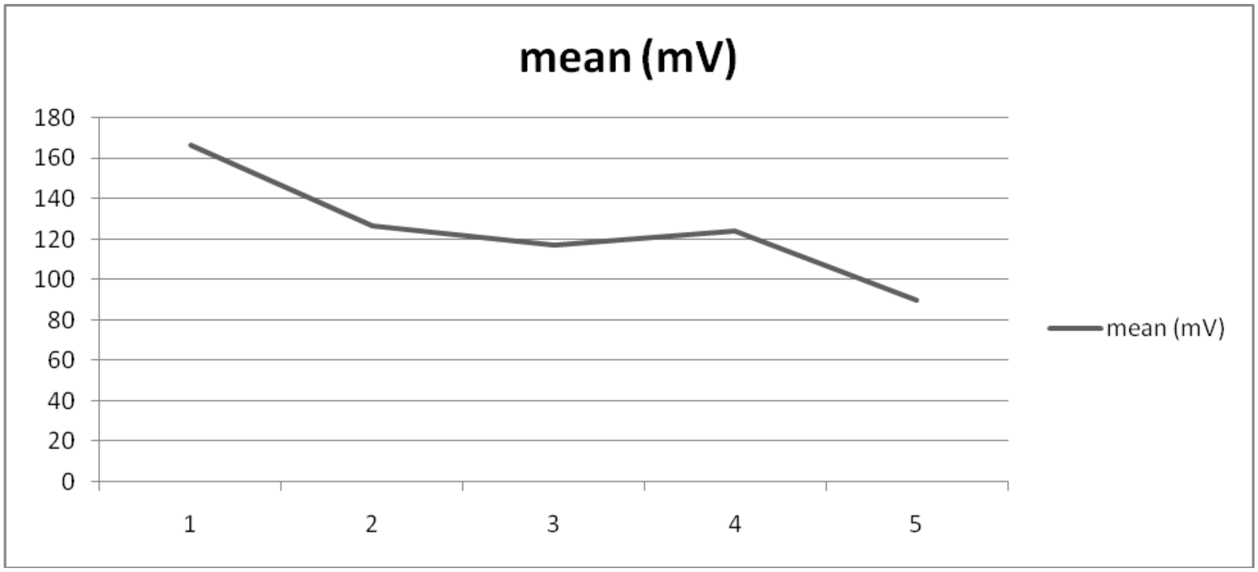

Chart 2. Showing the variation of Mean with respect to input frequency

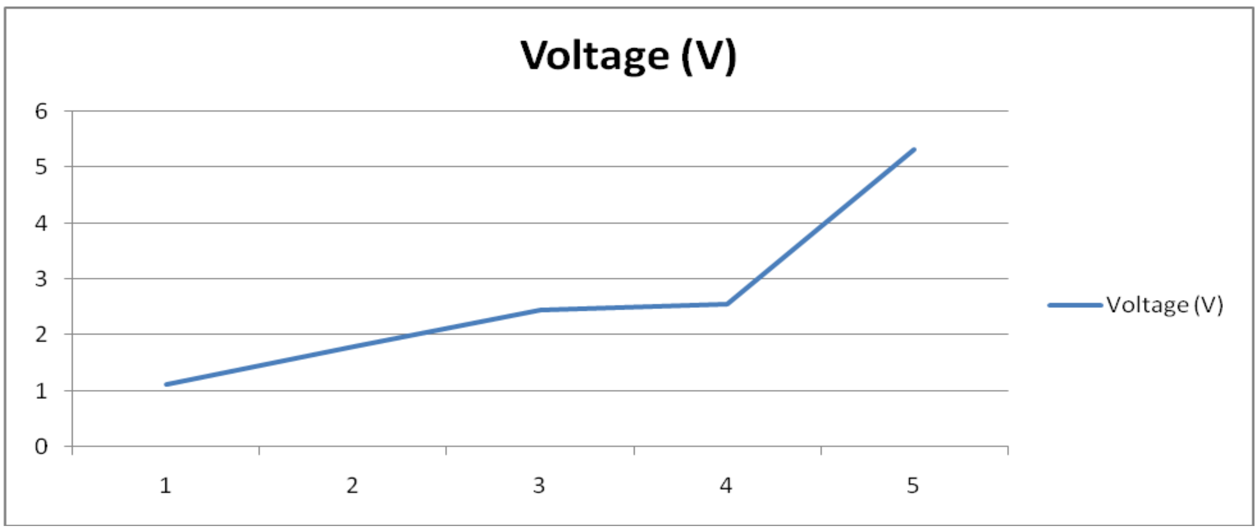

Chart 3. Showing the variation of Voltage with respect to input frequency

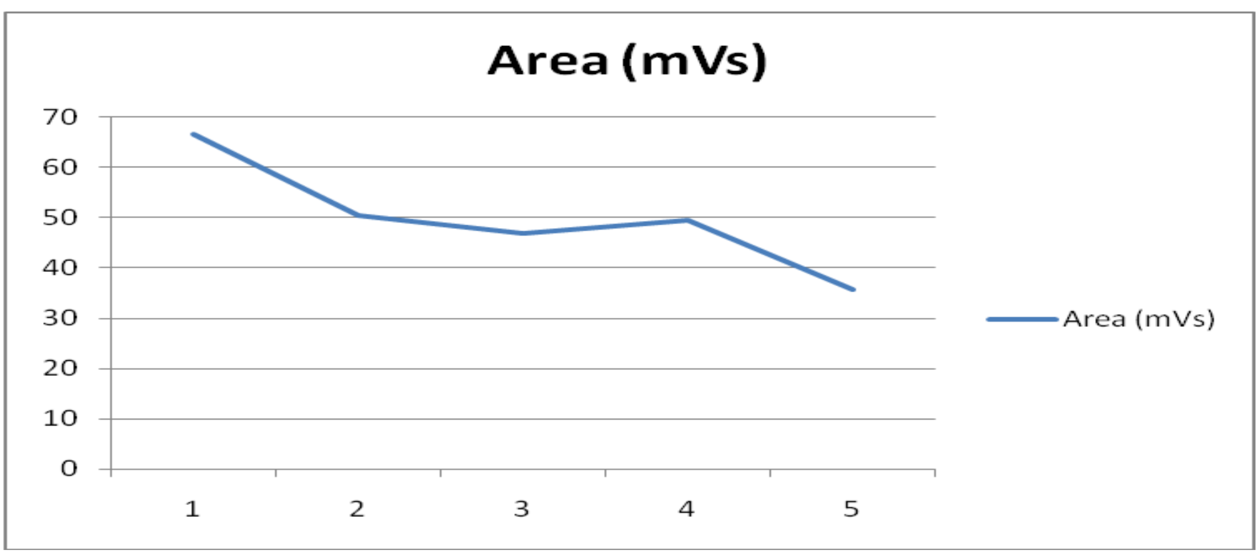

Chart 4. Showing the variation of Area of the Voltage signal with respect to input frequency

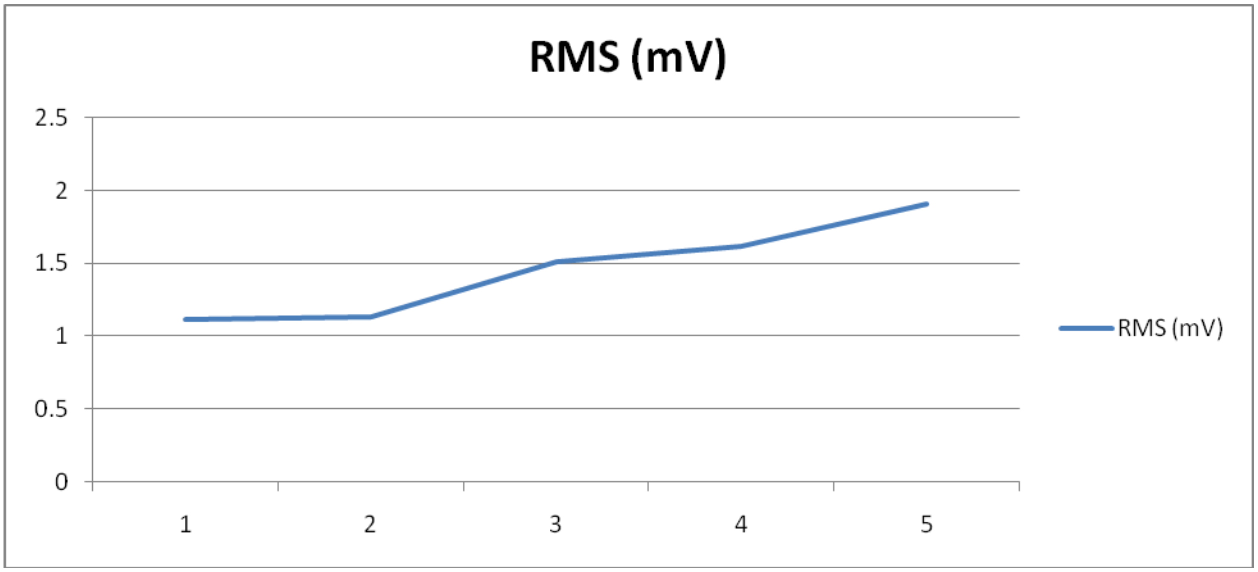

Chart 5. Showing the variation of RMS value of the Voltage signal with respect to input frequency

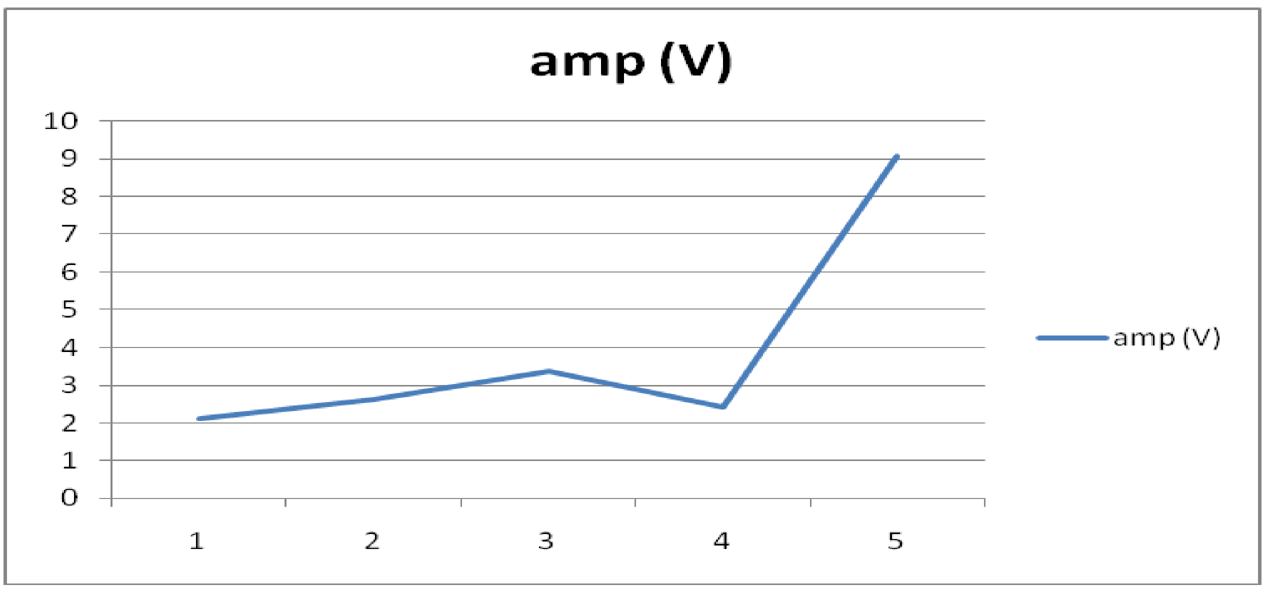

Chart 6. Showing the variation of Amplitude of the Voltage signal with respect to input frequency

DISCUSSION:

In the present study, we control the vibration in an alumunium beam element by applying counterforce. In finite element modelling using ANSYS, the location of piezo sensor was first determined. In the modelling, cantilever alumunium beam was subjected to a constant force of 9 N at the free end. The beam was divided into 1320 nodes. On a frequency variation of 0-100 Hz in 100 sub-steps, the readings of shear stress and displacement at each node was recorded. For 100 Hz frequency, it was found that the minimum value of shear stress was minimum at node 49. The maximum deflection was 0.0273 m. At different frequencies the voltage generated by piezo-electric patch was observed and noted down. Chart 1 is a plot between the maximum voltage generated and frequency input for the set of observation. Frequencies used were 12.5 Hz, 15 Hz, 17.5 Hz, 20 Hz, 22.5 Hz and 25 Hz. The voltages generated were in the reange of 1.7 V to

5.3 V. The graph obtained signifies that for increase in frequency input the maximum voltage value generated by the piezo-patch increases. Chart 2 is a plot between the mean voltage and frequency. For the same set of frequncies the mean voltage ranges were found to be between 90 to 170 mV. Here we obtain a decreasing trend. Chart 4 is a plot between the area of Voltage signal and input frequency where we find a decreasing trend. With decrease in frequency the area of voltage signal increased and the range was between 30 to 70 for the same set of frequency values. Chart 6 is a plot between the amplitude of voltage signal generated by piezo-electric patch and frequency input. The graph shows an increasing trend. As frequncy increases, amplitude of vibration obtained is greater.

CONCLUSION:

From the finite element analysis the location where the maximum value of shear stress is obtained was determined. From this, the optimal location of the sensor and actuator was found by taking into consideration the clamping area. From the experimental process, the volatage generated by the piezo-electric patch was obtained in variation with frequency input. It was found that if a sinusoidal waveform is provided, with increase in frequency the voltage generated by the piezo-electric patch increased. The plot between voltage generated and frequency input was almost an exponential curve. When we feed the voltage response of sensor into a control system, we generate a controlled output through the actuator, that can be used to control beam vibration actively.

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